The SciCryo Project and Cryogenic Scintillation of Al_2O_3 for Dark Matter

P. Di Stefano, N. Coron, P. de Marcillac, C. Dujardin, M. Luca, F. Petricca, F. Proebst, S. Vanzetto, M.-A. Verdier

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P.C.F. Di Stefano[⋆⋄], N. Coron[+], P. de Marcillac[+], C. Dujardin[○], M. Luca[⋆], F. Petricca[•], F. Proebst[•], S. Vanzetto[⋆], M.-A. Verdier[⋆] and the EDELWEISS collaboration[1]

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Abstract We discuss cryogenic scintillation of Al_2O_3. Room-temperature measurements with α particles are first carried out to study effect of Ti concentration on response. Measurements under X-rays between room temperature and 10 K confirm a doubling of light output. The integration of a scintillation-phonon detector into an ionization-phonon dark matter search is underway, and the quenching factor for neutrons has been verified.

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1 Introduction

Cryogenic experiments using ionization-phonon [1,2] or scintillation-phonon [3,4] detectors are among the most sensitive dark-matter searches thanks to their excellent rejection of the dominant, highly-ionizing background. Understanding other backgrounds, such as that produced by fast neutrons, searching for various WIMP couplings [5], and confirming evidence for detection will require a variety of target nuclei. The SciCryo project (IPN Lyon, IAS Orsay, MPP Munich and LPCML Lyon) is therefore investigating materials that could make suitable cryogenic scintillation-phonon detectors. Sapphire, for instance, is attractive because scattering kinematics and cross section make it a good detector to control the fast neutron background. Moreover, it is well-established as a cryogenic phonon detector for dark

⋆ Institut de Physique Nucléaire de Lyon, IPNL, UMR5822, CNRS-IN2P3, Université Claude Bernard Lyon 1, Université de Lyon, F-69622 Villeurbanne, France.
\+ Institut d'Astrophysique Spatiale, CNRS & Université Paris Sud, Bât. 121, Orsay, Cedex 91405, France.
○ Laboratoire de Physico-Chimie des Matériaux Luminescents - UMR 5620, Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France.
• Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany.
⋄ E-mail: distefano@ipnl.in2p3.fr

Sample	CLY (%)	Light detector	[Ti] (ppm)	[Cr] (ppm)
MPP-3	1.4	Si	68.4–72.5 (LA)	1.38–2.85 (LA)
MPP-4	1.4	Si	70.2–79.4 (LA)	1.43–1.9 (LA)
IAS-B213 [8]	1.3	Ge		
IAS-A104			5.11–6.98 (LA) 5.8 (GD)	0.27–0.44 (LA) 0.22 (GD)
IAS-A080 [8]	1.27	Ge	800–1200 (N)	
IPNL-1.3	0.8	Ge		
IPNL-1.2			<0.83–1.79 (LA) 1.1 (GD)	0.76–2.57 (LA) 0.34 (GD)
IAS-A107	0.25	Si		
IAS-A109			1.16–3.66 (LA)	0.55–1.74 (LA)

Table 1 Cryogenic γ scintillation collected-light yield (CLY, see text for definition) of various sapphire crystals. Crystals are grouped by supplier, a weak indication of composition. Concentrations of Ti and Cr are either nominal (N), or determined by laser-ablation-ICPMS (LA) or by glow-discharge-MS (GD) (for LA, range is spread of results over 5 measurement points; for GD, nominal error is ± 20 % of value). Yields vary by ≈ 6. For a given type of crystal, differences may arise from size, geometry and polish of samples, light collection efficiency and light detector. However, collected-light yields comparable to those of standard dark-matter detectors ($\approx 1.3\%$) are possible, both with Ge and Si light detectors.

matter[6,7], and certain samples have already been shown to scintillate at low temperature[8,9,10].

2 Crystals, doping and X-ray scintillation spectra

We have compiled the results of previous cryogenic experiments and performed some new ones to study the collected-light yield of various sapphire crystals. Collected-light yield here is understood as the fraction of energy that is deposited in a scintillator, transformed into light and detected by a calorimetric light detector[11]. It is not an absolute value, since a fraction of the light may be lost depending on the efficiency of the light detector and the setup. Results in Tab. 1 show a wide spread. However, several samples show a light yield comparable or better than the 1.3%[11] of the $CaWO_4$ already in use by some dark matter experiments[3].

We have recorded the scintillation spectra of many nominally pure sapphire crystals at room temperature under a strong flux of X-rays (for example, Fig. 1). These spectra are indicative of scintillation efficiency. Moreover, all spectra exhibit the presence of Ti^{3+} (wide band around 750 nm) and/or Cr^{3+} (line at 698 nm), dopants commonly used for sapphire laser rods. Though X-ray scintillation is very sensitive to small levels of impurities, it does not allow the quantification of the concentrations of dopants necessary to optimize light yield. In addition to their sensitivity, techniques to quantify traces in crystals have several different aspects: surface or bulk, destructive or non-destructive, sensitive to oxydation states or not. For sapphire, two commercially available methods, laser-ablation mass-spectrometry (LAMS) and glow-discharge mass-spectrometry (GDMS) are sensitive down to ppm levels. However, they are destructive, and do not distinguish between oxydation states such as Ti^{3+} and Ti^{4+}. We have therefore used two non-destructive optical methods sensitive to oxydation state: absorption and fluorescence. To carry out a systematic study of doping, a set of crystals has been obtained from ISC Kharkov scanning two parameters, the nominal concentration

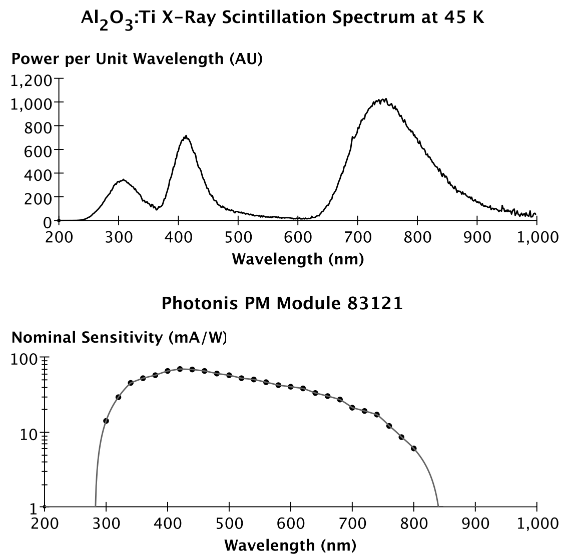

Fig. 1 Top: scintillation spectrum of an Al_2O_3:Ti sample at 45 K, measured under continuous X-ray stimulation with a monochromator and a CCD. Spectrum has been converted from intensity to power. Height of each band depends on doping of sample as well as redox potential. Bottom: sensitivity of PM used in subsequent tests with α particles and X-rays.

of Ti (10, 50, 100, 500 or 1000 ppm), and the redox potential under which the crystal is treated (−230 kJ/mol, −30 kJ/mol or 120 kJ/mol), affecting the fraction of Ti in the Ti^{3+} oxydation state. LAMS tests show the samples have at most 2 ppm of Cr; moreover, whatever Cr there is has a negligible contribution to their spectra (Fig. 1). Absorption and fluorescence properties of the samples, as well as X-ray scintillation spectra down to 50 K, will be described in a future publication [12].

3 Room-temperature α scintillation

The room-temperature response of several crystals to α particles has been tested using a Photonis 83121 photomultiplier module. Unlike standard photomultipliers, the one in this module has a multialkali photocathode which is fairly sensitive to the red light from Al_2O_3:Ti (Fig. 1). The module has a built-in high-voltage supply and 10 MHz amplifier. Moreover, the photocathode is transmission-type and deposited on the window of the PM, providing it with good geometrical efficiency. Crystals are pressed against the PM window by a white Delrin endcap. This allows comparison of the light yield of crystals of same geometry.

Tests have been performed using a ^{241}Am α source and several $5 \times 5 \times 1$ mm^3 samples. The particles hit the crystal on its large face opposite the window of the PM. Typical FWHM resolution on the α line is 10–15%. Responses of several samples are compared in Fig. 2. We note that the results have not been corrected for PM sensitivity (Fig. 1) which differs from that of a Si or Ge calorimetric light

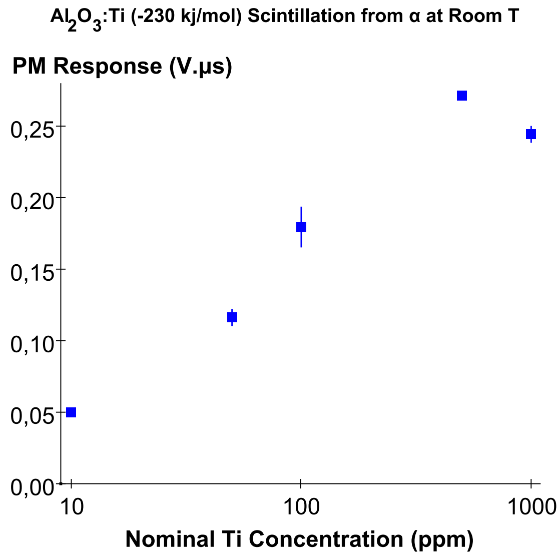

Fig. 2 Room-temperature response of various $5 \times 5 \times 1$ mm^3 Al_2O_3:Ti samples (230 kJ/mol) to α particles from a ^{241}Am source, as measured with the PM described in Fig. 1. Response is defined here as integral of PM pulse. Each measurement has been carried out twice.

detector or a CCD. Results may also differ under continous bombardment of other types of particles. Future work includes studying response to photons [12] and neutrons.

4 X-ray scintillation down to 10 K

The luminescence under X-ray bombardment of some samples has been measured down to 10 K using an optical cryostat. In this setup, X-rays from a tube operating at 35 mA current and 40 kV voltage enter the cryostat through an aluminium window and excite the $5 \times 5 \times 1$ mm^3 sample. Light escapes the cryostat through quartz windows and reaches the 83121 module outside, at room temperature. The module records the light emitted as the temperature of the sample changes. Temperature sweeps are carried out at 10 K/minute. During cooling, only luminescence is in play, whereas during warming, thermoluminescence can also be a factor. Results from a sample, measured without and with a 600 nm high pass filter, are shown in Fig. 3. The results show an increase of the light yield of about a factor two as the crystal is cooled to 10 K. This is in agreement with previous work [9]. Comparing the data with and without filter, and extrapolating to lower temperatures provides a hint that there may be a greater increase in store and that it may come from the short-wavelength component of the scintillation spectrum. Similar tests on other samples are in preparation.

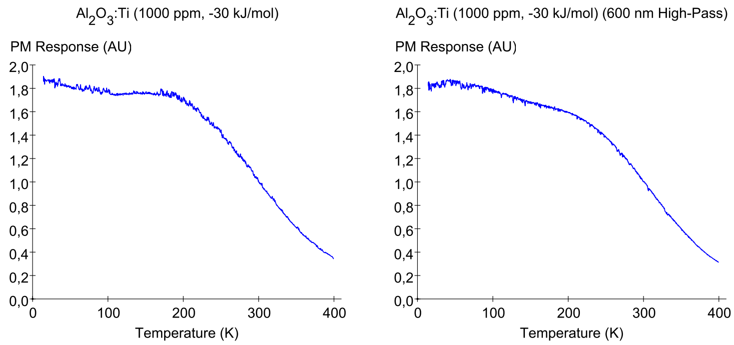

Fig. 3 PM response as a Al_2O_3:Ti (1000 ppm, -30 kJ/mol) sample is cooled under X-rays, with no filter (left) and with a 600 nm high-pass filter (right). Curves are normalized to a value of 1 at 300 K. Both show a gain of ≈ 2 at low temperature. A similar evolution is found for -230 kJ/mol crystals.

5 Integration of a detector into a dark matter experiment

We have integrated a scintillation-phonon detector into an ionization-phonon environment. This test is relevant for future large-scale cryogenic dark matter experiments such as EURECA [13] that may combine both technologies. The scintillation-phonon detector is a 50 g Al_2O_3 device previously characterized at surface level [8]. It has been installed in the low-background cryostat of the EDELWEISS II experiment at the Modane Underground Laboratory [14], after having been screened for radioactive background. Issues such as the mechanical, thermal and electrical compatibilities have been resolved. Performance of the phonon channel is on a par with that of the Ge ionization-phonon devices in the cryostat, with a baseline noise of 3 keV. The scintillation channel suffers from excess noise however, some of it coming from microphonics in the very small (195 mg) light detector, itself a calorimeter. Further work is necessary for the scintillation channel, as the overall background rejection threshold remains high (about 70 keV). Despite this, neutrons from calibrations with an AmBe source are clearly visible, thanks to the elastic scattering kinematics that favor Al_2O_3 over Ge. This amounts to ≈ 4 times more neutrons per unit volume visible in Al_2O_3 (100 keV threshold) than in Ge (30 keV threshold). The quenching factor for neutrons has been measured over the 500–1000 keV range to be 20 ± 2, compatible with the ground level value [8].

6 Conclusions

Systematic tests of the cryogenic scintillation properties of sapphire are underway with crystals of different Ti^{3+} concentrations. First results confirm that response to X-rays doubles when temperature goes down to 10 K. Tests at low temperature are necessary to establish a relationship between cryogenic light yield and doping concentrations. An integration test of a small cryogenic scintillation-phonon device into the ionization-phonon EDELWEISS experiment is progressing. It shows that sapphire can be useful to monitor the neutron background close to the germanium detectors.

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